Radio observations of gamma-ray blazars

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Abstract. Starting in 1991 we have performed a regular monitoring of EGRET sources with the Effelsberg 100-m telescope and the IRAM 30-m at Pico Veleta. In comparison with data on a sample of flat-spectrum quasars which have not been seen by EGRET we search for correlations of any kind in the behaviour of FSRQ's in the radio and gamma-ray regime. While there is no radio-to-gamma-ray luminosity correlation for these sources, it seems that gamma-ray high states coincide with increased activity in the radio regime with a strong tendency that gamma-ray outbursts precede radio outbursts. The gamma-ray spectra seem to harden with increasing flux level.

1. An example of an individual source: 0528+134

We will first discuss PKS 0528+134, the most luminous γ-ray source known besides γ-ray bursts. 0528+134 exhibits superluminal motion with $\beta_{app} \simeq 4.4$ and indications for even higher values (Pohl et al. 1995). Superluminal motion was expected since given the variability time scales of a day, the redshift of z=2.07 and the γ-ray flux in the OSSE range, strong Doppler boosting is required to satisfy the compactness limit and the Elliot-Shapiro relation (McNaron-Brown et al. 1995). It has been noted that the expulsion of new VLBI components may coincide with γ-ray outbursts (Pohl et al. 1996).
In Fig.1 we show the radio light curve of 0528+134 in comparison to its γ-ray state for the period 1991 to 1995. The source was quiet in the radio regime between 1985 and 1991 (Zhang et al. 1994). The following conclusion can be drawn: 0528+134 has been very bright in γ-rays either when it was weak in radio or a few months before a mm outburst. It was at medium γ-ray level at the time of the brightest ever-recorded radio outburst, at the end of 1995. Though the γ-ray high states seem to precede the radio outbursts, which is also supported by backextrapolation of the position of VLBI knots, there is no simple one-to-one relation. The analysis of individual sources is mainly hampered by the limited coverage of the γ-ray light curve and the problem that many sources

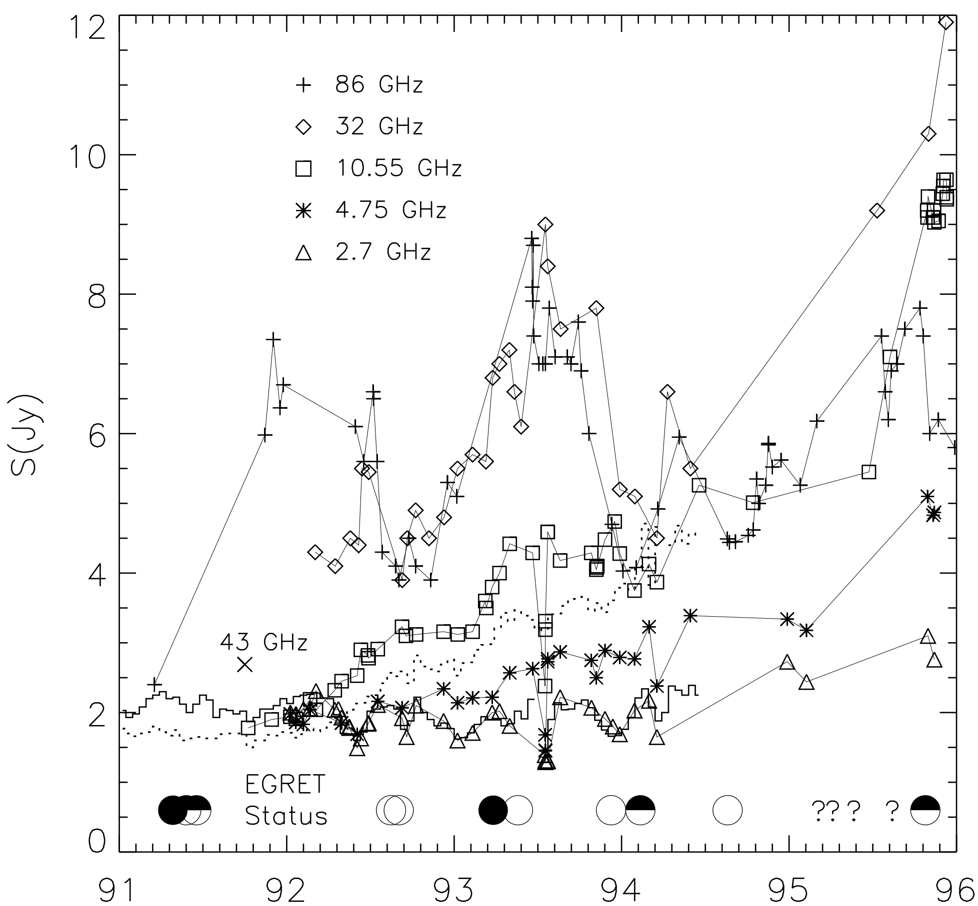

Figure 1. Here we show the radio light curve of 0528+134 based on Effelsberg data and observations at 86 GHz taken with the IRAM 30-m. The histograms give the two-weeks-averages of the NRL-GBI data at 2.25 GHz (solid line) and 8.3 GHz (dotted line). Observational uncertainties are below 5% except for the data at 32 GHz and 86 GHz which have uncertainty levels around 10%. The unusual depression in July 1993 is most likely an extreme scattering event and not intrinsic to the source. For comparison the state in the EGRET range is indicated by empty circles for low state ($S < 5 \cdot 10^{-7}$ ph. cm^{-2} sec^{-1} above 100 MeV), medium level ($S < 10^{-6}$), and high state ($S > 10^{-6}$). A question mark indicates protected data. It is tempting to relate the γ-ray outbursts in 1991 and 1993 to the mm outbursts a few month later. However, no strong γ-ray outburst has been reported yet for 1995, a few months before the brightest ever-recorded mm outburst. Or is there a time lag of two-and-a-half years, relating the 1991 γ-ray flare to the 1993 radio outburst, respectively the 1993 γ-ray flare to the 1995 radio outburst? Given the superluminal motion we would expect a corresponding VLBI knot to have a core separation of 0.3 mas after that time. In 1992.85 more than 80% of the 22 GHz flux was confined within 0.1 mas to the core (Pohl et al. 1995).

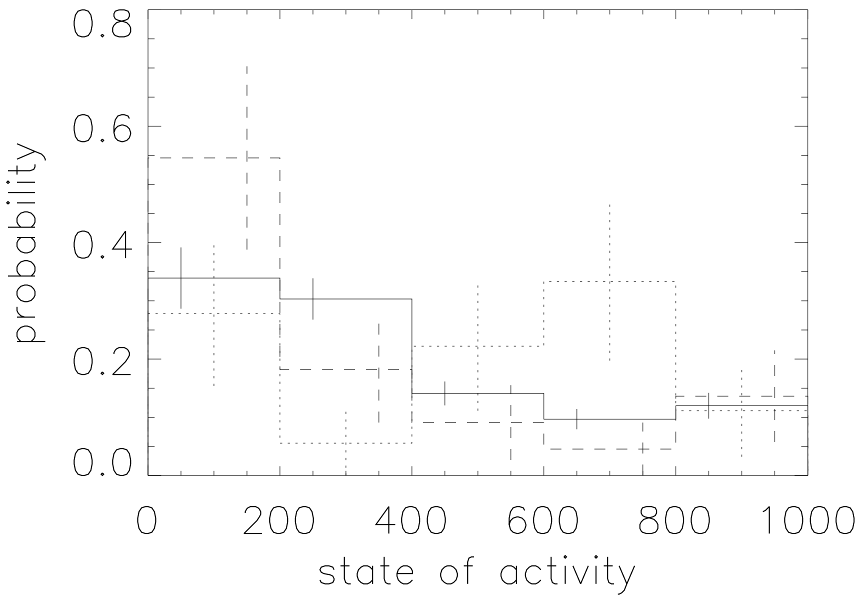

Figure 2. Activity state at 10 GHz simultaneous to EGRET detections (dotted line), averaged over the last three years for EGRET sources (solid line), and for a sample of FSRQ which have not been seen by EGRET. Activity in high-energy γ-rays coincides with activity in the radio regime.

– like 0528+134 – exhibit γ-ray variability on time scales of days, less than the standard integration time in EGRET observations.

2. The average source

We have seen that for an individual source it is difficult to relate γ-ray and radio outbursts to each other. This is especially true if the source is so active that the radio outbursts blend together.

To circumvent this problem we may also consider the average source. As the absolute flux levels of sources can be different and we are mainly interested in the variability behaviour we scale all flux values linearly between historical minimum and historical maximum. In this analysis we accept only sources which have been proven to be variable by at least a factor of two. During the EGRET sky survey we have observed all blazars with cataloged flux level >1 Jy simultaneously to the γ-ray observations. This allows us to compare the activity distribution in the radio regime of sources which have been seen by EGRET to those sources which have been γ-ray quiet. Here the activity of a source is defined on a scale of zero to thousand between historical minimum and maximum. The resulting activity distributions are shown in Fig.2 where in case of EGRET blazars we give both the activity at the time of γ-ray detection and the average activity over a three years time period. The average source has an enhanced activity

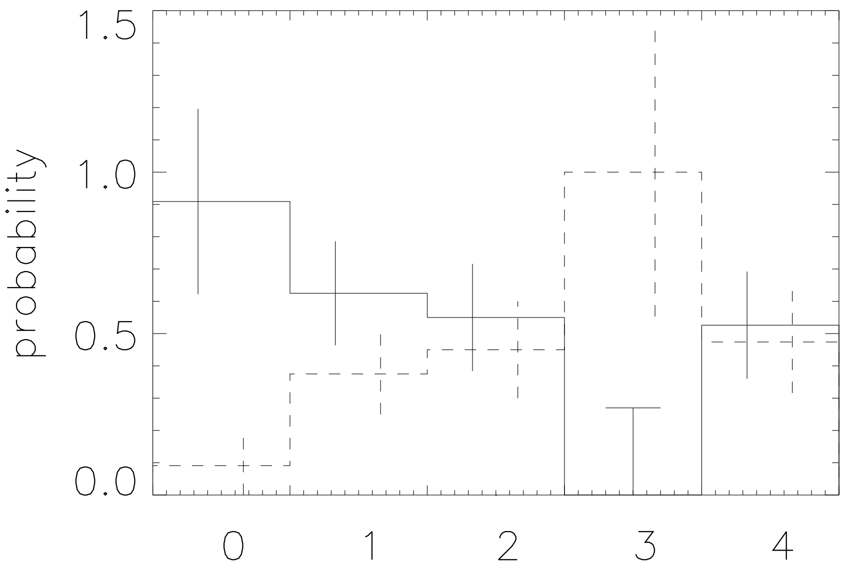

Figure 3. The probability level of detection (solid line) and non-detection (dashed line) of EGRET sources in different radio states: 0: increasing radio flux, 1: medium level without clear trend, 2: high state, 3: decreasing flux, 4: low state. There is a high probability level for detection at increasing radio flux, i.e. in the rising phase of a radio outburst, and a correspondingly small detection probability in the declining phase of radio outbursts.

level at radio wavelengths when it is bright in high energy γ-rays (Mücke et al. 1996a)

Most EGRET blazars are variable at γ-ray energies. It may be instructive to see whether there is a relation between the radio state and the γ-ray brightness. The γ-ray data for this analysis are taken from the second EGRET catalog (Thompson et al. 1995) where we have excluded observations with large off-axis angles which often yield only poor upper limits. Then the significance of detection is used as discriminator between γ-ray bright and γ-ray quiet. As can be seen in Fig.3, there seems to be a clear trend, indicating that γ-ray outbursts precede radio outbursts: when the radio flux is increasing, the average source is preferentially bright in γ-rays, and when the radio flux is decreasing, the average source is preferentially weak in γ-rays (Mücke et al. 1996a). We have also searched for correlations between radio and γ-ray quantities as well as between flux and spectral indices. There is no simple relation between the scaled γ-ray flux and the scaled radio flux or scaled radio spectral index. However, we found evidence for a relation between the γ-ray flux and the γ-ray spectral index. This can be seen in Fig.4 where both the γ-ray flux and the power-law spectral index have been scaled between historical minimum and maximum. The average source appears to have a harder spectrum at γ-ray high states (Mücke et al. 1996b). The chance probability is of order 10^{-5} and the result is also stable against the omission of individual sources from the sample.

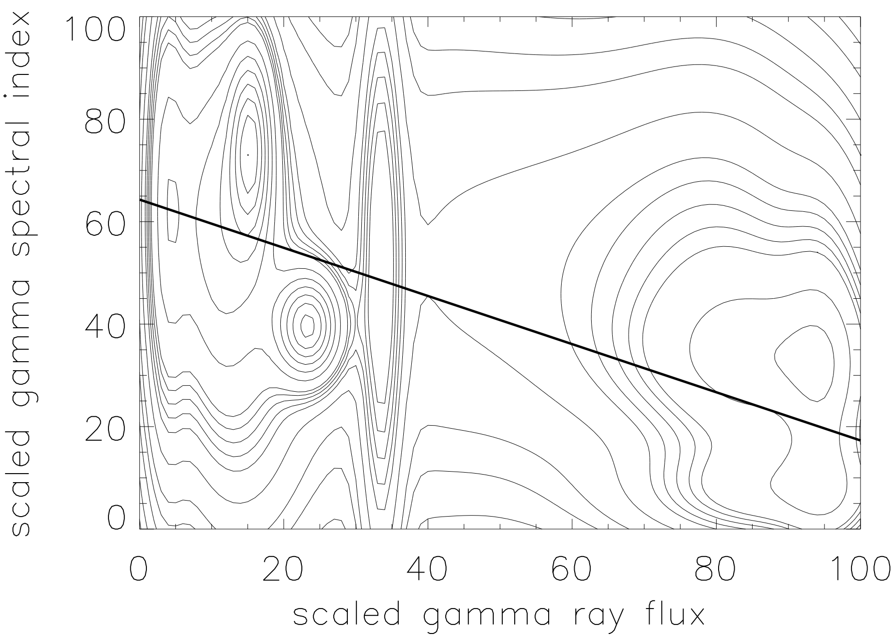

Figure 4. Scaled γ-ray spectral index (0=hardest occurance minus 1σ, 100=softest occurance plus 1σ) in comparison to the γ-ray flux. Here the data are represented by ellipsoidal Gaussians and the fit is based on χ^2 statistic.

3. Luminosity correlations

There is no luminosity correlation between radio and γ-ray emission of blazars. We have analysed our data with Spearman's correlation method and, to include also the upper limits, by Kendall's τ. These partial correlation coefficients take care of the strong redshift dependence of luminosity, which may mimic a correlation for flux-limited data. In case of the radio-to-γ-ray relation of blazars the apparent alignment of data in luminosity-luminosity diagrams is indeed an artefact arising from sensitivity limits in the sample (Mücke et al. 1996c). For EGRET observations the sensitivity limit is mainly given by count statistic, while in the radio range mainly a credibility limit applies, that in view of their abundance one is reluctant to identify a γ-ray point source with a 100 mJy radio source, apart from the fact that catalogs including spectral information are not complete at these flux levels.
The results of our analysis are summarized in Table 1. We have also compared peak luminosities, here based on radio data taken from the literature. The marginal correlation signal for the 4.8 GHz data is not supported by a similar result for the 8 GHz data and thus probably a statistical fluke.
When averaging over the light curves, i.e. using mean values, the dynamical range gets even more compressed so that a positive correlation signal is artificially produced, though the original data are uncorrelated. Our simulations

Table 1. Results of the correlation analysis of N simultaneously observed data points: partial correlation analysis using the Spearman rank order coefficient R_s or Kendall's τ for the case of censored data (i.e. including upper limits: UL). The third column gives the resultant correlation coefficient and the fourth column the chance probability of erroneously rejecting the null hypothesis. An asterisk indicates that the chance probability is determined on the basis of simulations. The analysis was carried out between the logarithms of the luminosities and K-corrected flux densities, respectively.

data	N	CC	prob.	correlation
10 GHz - γ-ray (simult.)	25	0.158	0.465	NO
10 GHz - γ-ray (simult.+UL)	42	0.079	0.288	NO
2.7 GHz - γ-ray (simult.)	22	0.046	0.751	NO
2.7 GHz - γ-ray (simult.+UL)	41	0.063	0.426	NO
max. 4.8 GHz - γ-ray	12	0.594	0.053	marginal
max. 8 GHz - γ-ray	11	0.363	0.314	NO
4.8 GHz - γ-ray obs. (mean)	38	0.347	0.12 $*$	NO
8 GHz - γ-ray obs. (mean)	28	0.405	0.11 $*$	NO

show that the chance probability for a high correlation coefficient is increased roughly by a factor 4 compared to the standard R_s statistic. This may explain earlier claims for a correlation (Stecker et al. 1993; Padovani et al. 1993).
We also searched for linear correlations by a χ^2 test on the flux-flux relation. In no case we obtained acceptable fits of linear relations to the observed simultaneous data.

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